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Pre–Colorado River drainage in western Grand Canyon: Potential influence on Miocene stratigraphy in Grand Wash Trough

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ABSTRACT

A model is proposed whereby a Miocene Colorado River precursor canyon, deeper than 600 m, formed on the western Hualapai Plateau by headward erosion along a strike-valley drainage. Basin and Range faulting of the margin of the Colorado Plateau initiated canyon formation. This canyon was occupied by a long narrow lake, and the surface of the lake was at or above the level of the Hualapai Limestone. Such a hypothesized lake would have trapped any coarse sediment derived from the surrounding basin at the head of the lake, well upstream from the Grand Wash Trough. The drainage area feeding into the lake would have included the Hualapai Plateau and the combined ancestral drainages of Kanab and Cataract Creeks. This >13,000 km² basin has been dominated by surface exposures of Paleozoic carbonates since at least late Eocene time and generates no more than 1%–2% of the runoff associated with the modern (predam) Colorado River discharge. Such a carbonate-dominated, sediment-deficient basin would supply carbonate-rich runoff to the structural depocenter in the Grand Wash Trough, possibly explaining the upward transition to the Hualapai Limestone facies in late Miocene time. The upstream canyon delta produced in this proposed model could have been removed by the Pliocene-Pleistocene integration and younger incision of the more powerful, modern Colorado River.

Keywords: Grand Canyon, Hualapai Plateau drainage, Miocene, Muddy Creek Formation.

INTRODUCTION

The region near the mouth of western Grand Canyon, where the Colorado River exits from the Hualapai Plateau into the Grand Wash Trough (Fig. 1), contains the key geologic relationships that have shaped many geologists' perceptions of the origin of the Colorado River as a throughflowing drainage system since the work of Longwell (1936). The interior basin Muddy Creek Formation and its correlatives in the Lake Mead–Grand Wash Trough region, capped by the Hualapai Limestone, have been considered as proof that no large river like the modern Colorado exited from the Hualapai Plateau into the Grand Wash Trough until late

Miocene time. This scenario includes the implicit assumption by some geologists that a large gorge, like that associated with the modern Grand Canyon, also was not present until the throughflowing Colorado River became established in late Miocene time.

The prevailing view for many decades has been that the western Grand Canyon must have been incised relatively rapidly by an emerging Colorado River drainage system so large that it would have left a record of deposition in the Grand Wash Trough consisting of voluminous clastic deltaic deposits and coarse gravels derived from upstream reaches on the adjacent Colorado Plateau (Figs. 1–3). No such sedimentary record is present in the partially eroded Miocene sedimentary sequence in the Grand
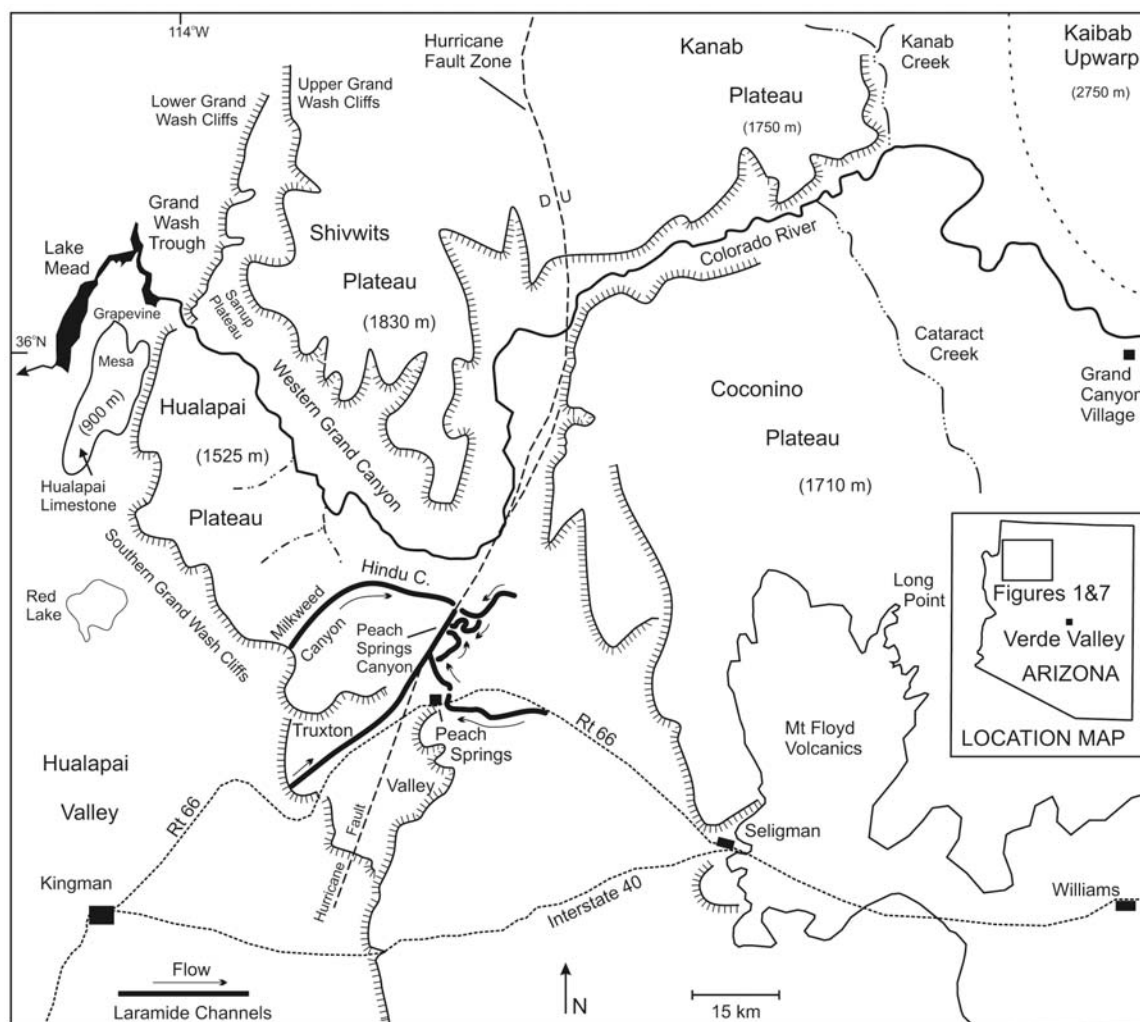
Figure 1. Regional physiography and selected place names for the western Grand Canyon and southwestern Colorado Plateau margin. Wide black lines are individual Laramide canyons with flow arrows based on imbrication measurements. The Hualapai Plateau is a structural (cuestaform) bench formed by the northeast recession of the Shivwits Plateau scarp. The distance between the Laramide Hindu Canyon and the modern Colorado River indicates the inferred amount of scarp recession between the creation of the two drainage systems.

Wash Trough near the mouth of the Grand Canyon, where the Miocene stratigraphic section fines upward into the Hualapai Limestone (Fig. 2). The Hualapai Limestone in the Grand Wash Trough reflects a restricted freshwater environment with limited sediment input, in contrast to the clastic sediments below, as summarized by Faulds et al. (1997, 2001a). The assumption that an early Colorado River or a possible precursor stream was absent during most of this Miocene interval seems reasonable from a simplistic viewpoint, despite the fact that much of the Hualapai Limestone and underlying Miocene sediments are eroded from the immediate vicinity of the mouth of Grand Canyon. The closest thick exposure of Hualapai Limestone is on Grapevine Mesa, nearly 11 km west of the mouth of Grand Canyon (Figs. 1 and 2).

Longwell (1936) and Lucchitta (1966, 1972, 1979) pointed out that much of the Miocene sediment in the Grand Wash Trough represents large alluvial fans that prograded into the Grand Wash

Trough from the higher terrain to the west and extended eastward to the very edge of the Hualapai Plateau (Fig. 2). The facies relationships appear incompatible with a large drainage system, such as the Colorado River, flowing westward off the Colorado Plateau in early or middle Miocene time. The recently published map by Wallace et al. (2005) of the Meadview North Quadrangle, southwest of the canyon mouth, contains detailed cross sections of the facies relations at Grapevine Mesa south of Lake Mead (Figs. 1 and 2). The geology of the Grand Wash Trough north of Lake Mead has recently been compiled on a map with cross sections by Billingsley et al. (2004).

There are plausible alternative explanations to some of the prevailing assumptions about Miocene sedimentation and Miocene facies trends in the Grand Wash Trough that are linked to the Laramide history and the inherited Laramide physiography of the adjacent Hualapai Plateau. For the purposes of this discussion,
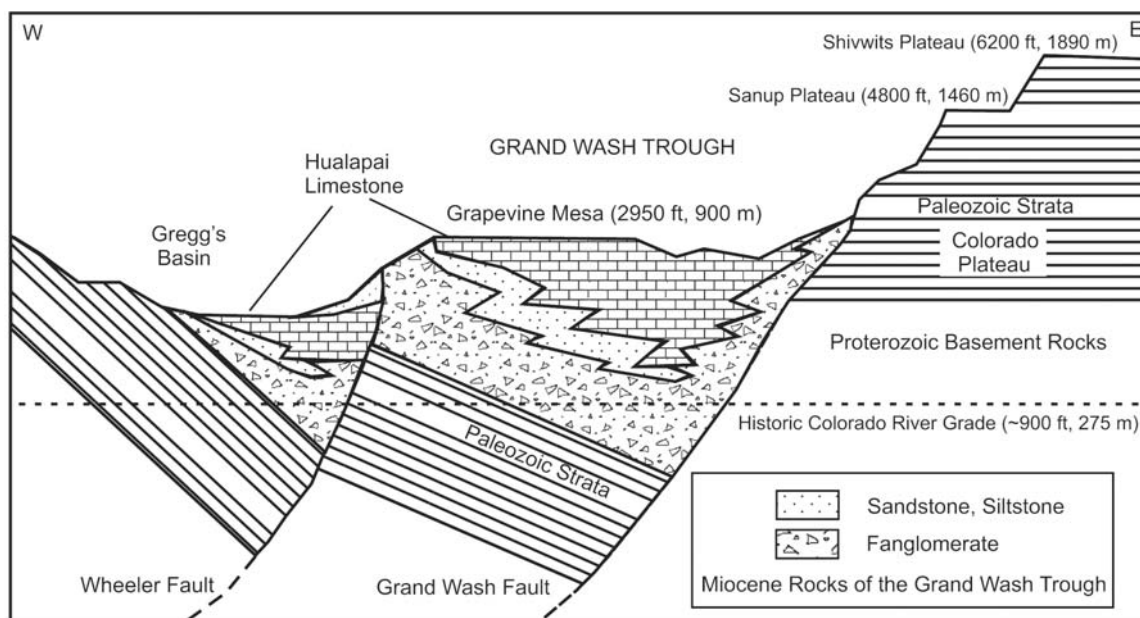
Figure 2. Simplified cross-section view of the Miocene basin fill in the Grand Wash Trough, 10 km west southwest of the mouth of Grand Canyon. Sanup Plateau is a local term referring to narrow erosional bench at same elevation as Hualapai Plateau but on north side of Colorado River (see also Fig. 1). Geology was modified from Lucchitta (1979). See Wallace et al. (2005) for more detail.

the Laramide orogeny in Arizona includes events from Campanian through middle Eocene time, bracketed between 80 Ma and 40 Ma. The age assignment for Laramide sediments in the Hualapai-Coconino Plateau region (Figs. 1, 3, and 4) is based on fossil gastropods and charophytes in freshwater limestones located within arkosic gravels at Long Point (Young, 2001b; Young et al., 2007), which indicate a late Paleocene or early Eocene age (ca. 50–60 Ma). The arkosic gravels themselves (Fig. 4) contain numerous volcanic clasts with K-Ar ages most commonly in the range from 65 to 84 Ma (Young, 2001b; Priest, 2001). However, the initiation of Late Cretaceous(?) erosion and the cessation of Laramide deposition on the Hualapai and Coconino Plateaus (Figs. 1 and 3) are relatively unconstrained in time, except by inference from the chronology of regional Laramide volcanism and tectonism (Damon and Mauger, 1966).

The Laramide physiographic genesis of the adjacent Hualapai and Shivwits Plateaus provides compelling evidence for the probable emergence of an incised, middle Miocene, western precursor to the modern Grand Canyon, without necessitating the contemporaneous, voluminous deposition of middle and late Miocene clastic deltaic or conglomeratic facies in the preserved Grand Wash Trough sediments near the mouth of the modern canyon. The purpose of this review of published areal studies and regional compilations is to develop an alternative model that accounts for some of the presumed obstacles to the gradual transformation of a northeast-sloping Laramide landscape to the present-day, southwest-draining Colorado River Basin. The proposed model focuses specifically on the issue of whether a middle Miocene precursor canyon on the Hualapai Plateau is nec-

essarily incompatible with the observable stratigraphic sequence in the Grand Wash Trough.

MIOCENE GEOLOGY AND REVISED NOMENCLATURE, WESTERN LAKE MEAD

Bohannon (1984) reviewed the nomenclature issues associated with the sediments of Muddy Creek age (Fig. 2) in the Lake Mead region and pointed out that no adequate type locality for the Miocene Muddy Creek Formation was originally designated. Stock (1921) originally used the term "Muddy Creek" to describe rocks north of Overton, Nevada. Several authors subsequently applied the term to relatively undeformed Tertiary sediments that underlie the Hualapai Limestone of Longwell (1936) throughout the region west of the Grand Wash Trough. Bohannon (1984) noted that the Hualapai Limestone in the Grand Wash Trough near the mouth of Grand Canyon is interbedded with red sandstone near its base that traditionally has been termed "Muddy Creek," and that both deposits were designated as members of the Muddy Creek Formation (Longwell, 1936; Lucchitta, 1966, 1972; Blair and Armstrong, 1979). However, Bohannon argued that the red sandstone in the Grand Wash Trough is slightly older than the Muddy Creek Formation at its principal reference section (Bohannon, 1984). Therefore, Bohannon recommended returning the Hualapai Limestone to formational status and designated the sediments below the Hualapai Limestone in the Grand Wash Trough as the "rocks of the Grand Wash Trough" (p. 9), because they are not physically continuous with the principal reference
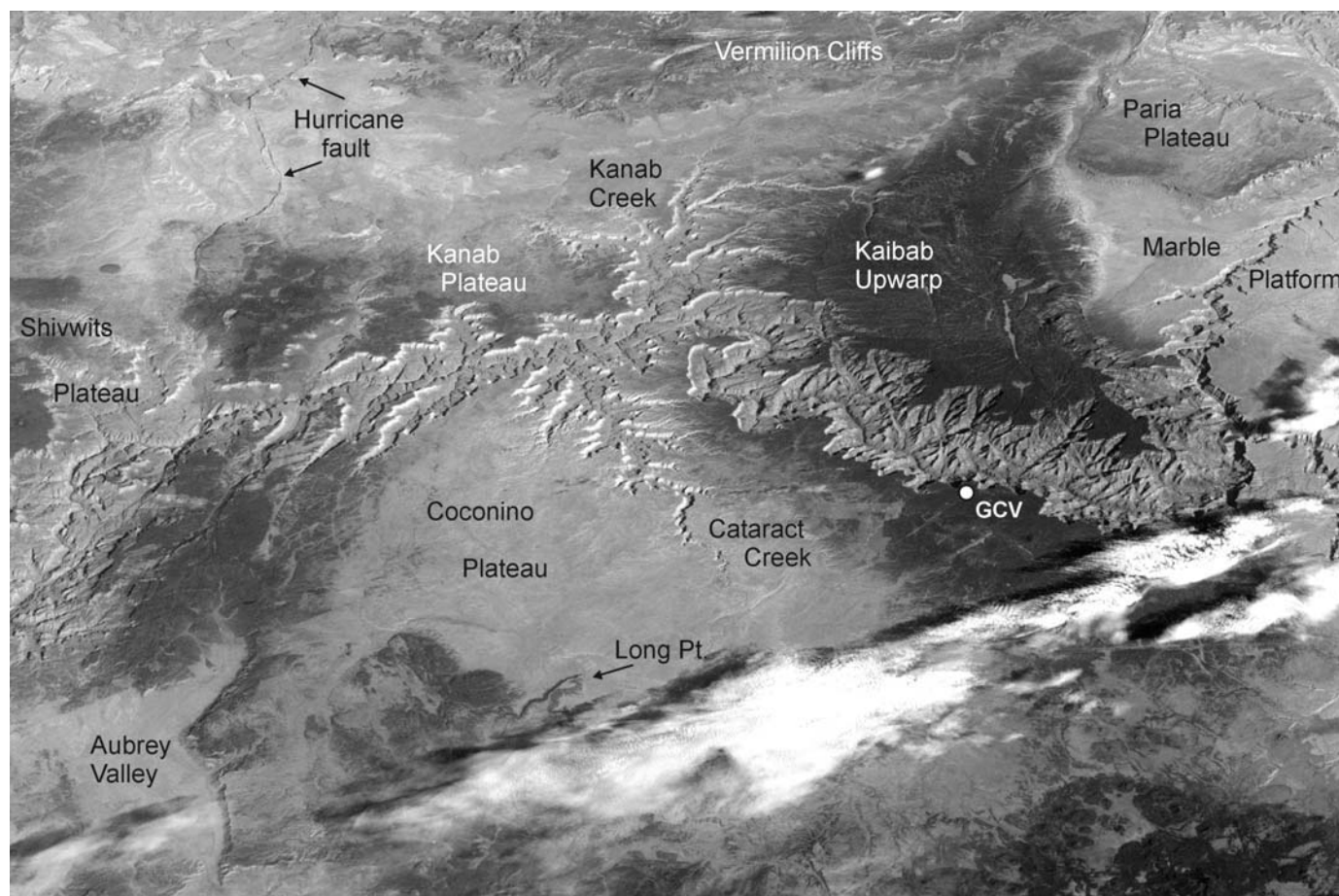
Figure 3. National Aeronautic and Space Administration (NASA) image of key structural features and physiography between the Kaibab Upwarp and the Hurricane fault discussed in text. Paleogene lacustrine sediments interbedded with arkosic sediments are capped by Miocene basalts at Long Point (see also Fig. 1). NASA photograph STS073-E-5295 (converted to gray scale). GCV—Grand Canyon Village; Pt.—Point. Width of view at center is 162 km. GCV = 36.058° N lat, 112.122° W long.

section of the Muddy Creek sediments further to the west. Recent field mapping has followed Bohannon's usage and excluded the Grand Wash sediments from the Muddy Creek Formation proper (Wallace et al., 2005; Billingsley et al., 2004). Although the Hualapai Limestone now has formation status in the Grand Wash Trough, its base is transitional with the underlying clastic sediments that were once included in the Muddy Creek Formation.

Despite these refinements in understanding the details of the Miocene stratigraphy, the Miocene section in the Grand Wash Trough has been referred to routinely as "Muddy Creek" in the geologic literature throughout the period from the 1930s through the 1990s (Hunt, 1969). This results largely from the extensive references in the literature on the Grand Canyon to the "Muddy Creek problem," based on the recognition by Longwell that the younger Colorado River course had been incised into the sediments he mapped as the Muddy Creek Formation and the Hualapai Limestone throughout the Lake Mead region.

Faulds et al. (2001a) summarized the evidence that the Hualapai Limestone in the Grand Wash Trough is correlative with the recognized Hualapai Limestone in Gregg's Basin immediately to the west (Fig. 2). The age of the Hualapai Limestone is bracketed by ages of ca. 11–5.97 Ma throughout the Lake Mead region (Faulds et al., 2001a; Spencer et al., 2001). The base of the limestone is gradational with the underlying clastic sediments in all of the subadjacent basins throughout the Lake Mead region.

Faulds et al. (2001b) dated Basin and Range extensional faulting in the Grand Wash region as beginning at 16.5 Ma, peaking prior to 13 Ma, and ceasing between 11 Ma and 8 Ma. All of the recognized Muddy Creek deposits and their generally little-deformed, late Miocene correlatives in the Lake Mead–Grand Wash region are nearly horizontal and clearly postdate the main phase of Basin and Range faulting. Muddy Creek–age sediments rest unconformably upon older, tilted Tertiary rocks north of Lake Mead, such as the early Miocene Rainbow Gardens Member of the Horse Springs Formation, which ranges from 18.8 Ma to older than 26 Ma (Beard, 1996; Billingsley et al., 2004).
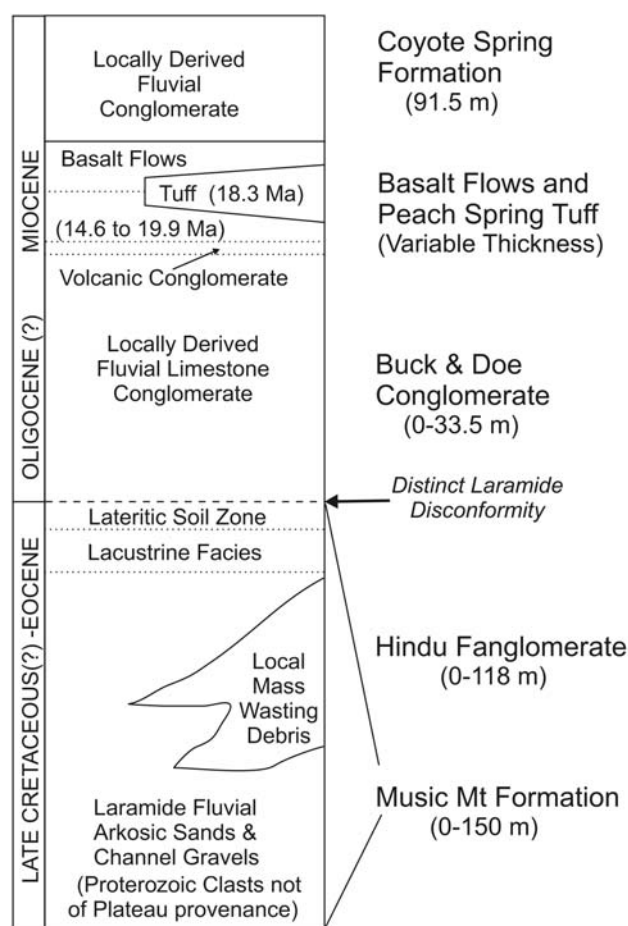
Figure 4. Schematic stratigraphic column of Cretaceous(?)-Tertiary deposits of the Hualapai Plateau. These sediments and volcanic rocks are thickest in Laramide paleochannels at Peach Springs and Milkweed-Hindu Canyons. Dotted lines indicate gradational contacts. Dashed lines are unconformable contacts. Solid lines are distinct lithologic changes. Type localities, detailed facies descriptions, and revised nomenclature are in Young (1999).

For the purpose of simplifying this discussion, "Muddy Creek time" is informally considered to include the interval of middle to late Miocene time when the post–Basin and Range, near-horizontal rocks, capped by the Hualapai Limestone, were deposited in the Grand Wash Trough at the edge of the Hualapai Plateau. This paper presents a logical, alternative explanation for the apparent lack of deltaic sediments with obvious Colorado Plateau provenance in the Muddy Creek–age rocks of the Grand Wash Trough, including the Hualapai Limestone and the middle Miocene basin deposits directly beneath it. The lack of a direct stratigraphic connection between the Grand Wash Trough sediments and the true Muddy Creek Formation in basins immediately to the west is not a significant issue for the concepts discussed in this paper insofar as the Grand Wash Trough sediments and the similar Miocene sediments in adjacent basins are obviously very close in age.

EARLY TO MIDDLE TERTIARY DRAINAGE HISTORY

Southwestern Colorado Plateau

The circumstantial evidence for a Laramide terrestrial depocenter across the southwestern Colorado Plateau region in Paleogene time is described by Young (2001b). The resulting so-called arkosic "Rim gravels" (Cooley and Davidson, 1963), which must have buried much of northern Arizona and southern Utah, are essentially correlative with the Claron Formation and associated early Tertiary sediments in southern Utah (Goldstrand, 1990). Young describes the evidence for assigning thin fossiliferous limestones in the uppermost arkosic fluvial sediments on the Coconino Plateau at Long Point (Figs. 1 and 3) to late Paleocene or early Eocene time (Young, 2001b; Billingsley et al., 2006; Young et al., 2007). This indicates that the earlier Laramide erosion of the Colorado Plateau occurred in Paleocene or Late Cretaceous time. Ongoing erosion of these Laramide sediments exposed a regional, step-bench topography in northern Arizona developed on Mesozoic and older sedimentary rocks that were buried by debris shed off the higher Laramide terranes to the west and south (Figs. 3–6).

It is unclear precisely how and when most of the early post-Laramide removal of these thick arkosic sediments was accomplished and whether the erosion occurred before middle Miocene time, when no Colorado River outlet is assumed to have been present on the western Colorado Plateau. However, remnants of arkosic Laramide sediments still covered portions of the western Colorado Plateau when early to middle Miocene lavas were erupted around the southwestern plateau margin (Young and McKee, 1978). At some undetermined time, when these arkosic Laramide sediments were probably being reworked by local drainage reorganization, the onset of Basin and Range extension created the structural relief that permitted local runoff to significantly increase headward incision by streams along the Hualapai Plateau margin at the Grand Wash Trough. Local drainage expansion, maintained by local precipitation, gradually evolved throughout the region between the Kaibab Upwarp and the Grand Wash Trough during a poorly defined Oligocene-Miocene erosion interval. It must be assumed that many other independent subbasins throughout the emerging Colorado River system were undergoing active reorganization during this same interval, whether or not they closely resembled the modern Colorado River drainage.

Kanab-Coconino Plateaus

The appearance of an integrated throughflowing Colorado River in the western Grand Canyon region sometimes is viewed simplistically as the result of uplift accompanied by coincident downcutting, implying that an integrated river system was present prior to Colorado Plateau uplift (Dutton, 1882). Improved chronology has produced modified theories that an upper and lower Colorado River evolved independently after a period of implied Miocene drainage "stagnation" (McKee et al., 1967). Subsequent workers have suggested that headward erosion and
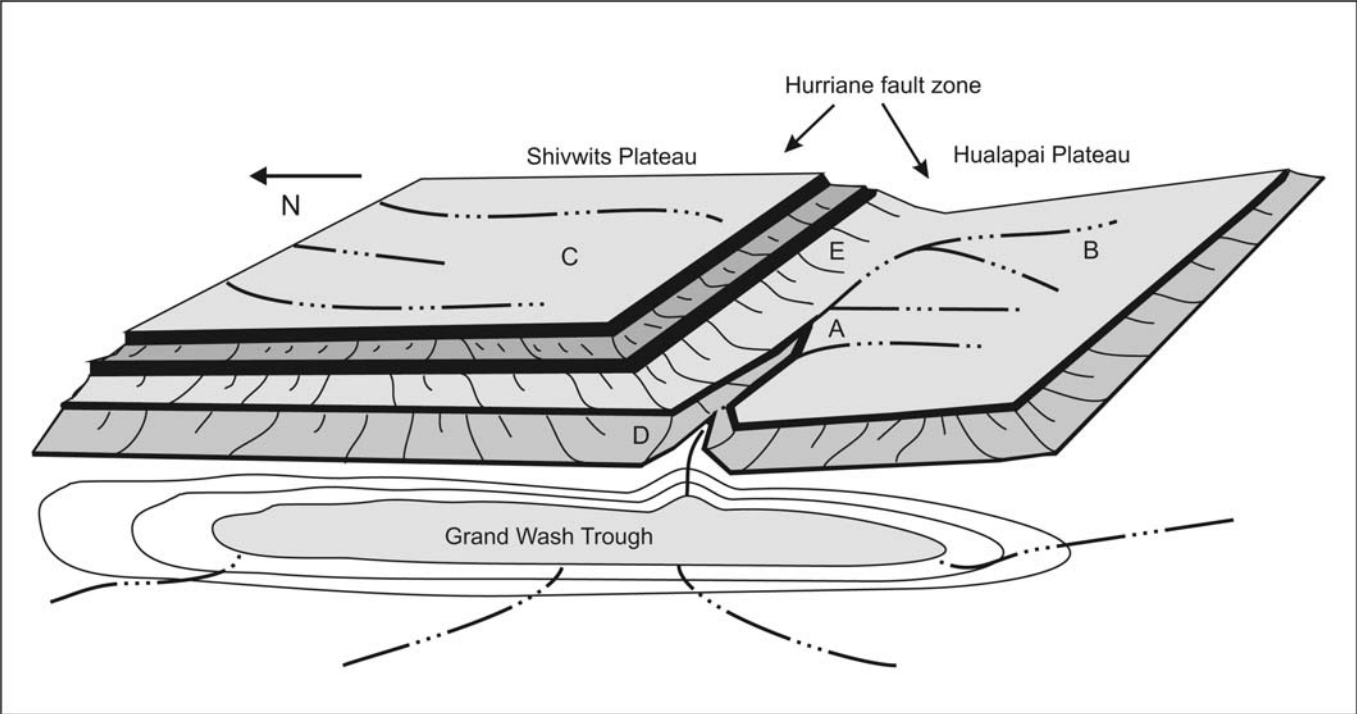
Figure 5. Schematic perspective view of initial canyon incision (A to D) on Hualapai Plateau (B) at base of retreating scarp (E) of Shivwits Plateau (C) with interior draining basin in Grand Wash Trough in foreground. Tributary drainage (B) parallel to regional dip provides necessary runoff for effective headward erosion (knickpoint migration). Back edge of diagram corresponds to approximate location of Hurricane fault.

Figure 6. Relationship of physiographic features of the western Grand Canyon region to schematic stratigraphic column. Dashed lines between rock formations indicate unconformities.

basin overflow both may have been important aspects of drainage integration (Scarborough, 2001; Spencer and Pearthree, 2001; Meek and Douglas, 2001). However, these solutions give inadequate attention to the requirement that upstream tributary basins must have coexisted in 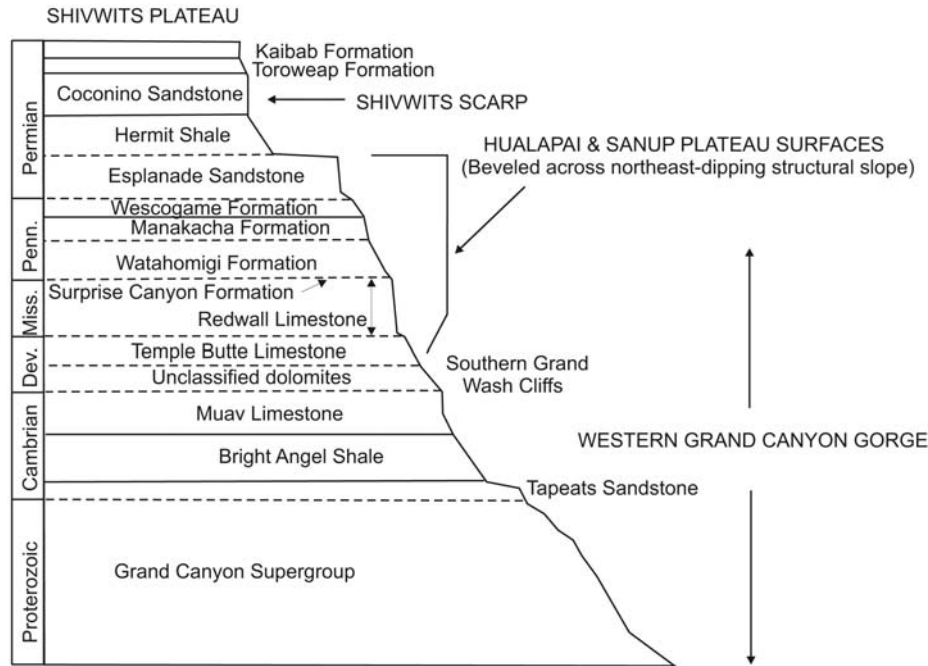an evolutionary continuum during mid-Tertiary time throughout the modern Colorado River Basin. These subbasins must have evolved and gradually merged into a modern regional drainage throughout some ill-defined post-Laramide interval. It is also now clear that most of the regional uplift of the southwestern Colorado Plateau margin, which is postulated to have driven the process of canyon formation, did not occur during late Neogene time but was mainly associated with Laramide deformation (Young, 2001a, 2001b).

The evolution of a regional drainage system in a diverse region with variable structural elements inherited from Laramide or older events must include a gradual integration of unrelated tributaries, the patterns of which conformed to the local dip slopes and paleotopography, as described for east-central Arizona by Potochnik (2001). For example, tributary drainage off the eastern and western slopes of the Kaibab Upwarp (Figs. 1 and 3) would have evolved under any local precipitation regime, independently of the presence or absence of a Colorado River. The same would be true for drainage conforming to the broad, northeast-dipping surface of the Coconino Plateau (Figs. 1 and 3).

The ancestral origins of the modern drainages that evolved between the Kaibab Upwarp and the Hurricane fault can be envisioned by considering the simple structural elements that constrain the drainages of Kanab and Cataract Creeks (Figs. 1 and 3). These two subbasins conform to the broad synclinal trough created between the northeast regional dip of the Paleozoic rocks and the reversed dips along the western flank of the Kaibab Upwarp, both of which are artifacts of Laramide deformation. These modern tributaries to the Colorado River would have gradually evolved contemporaneously with the removal of the Laramide arkosic sediments that blanketed much of the region through middle Miocene time, regardless of whether or not a Grand Canyon was present.

These reasonable assumptions leave unanswered the issue of how and when such fragmented drainages, or any emerging Colorado River, might have expanded or exited the Coconino-Kanab Plateau region. One alternative is that local streams became temporarily ponded in one or more shallow basins until a better integrated drainage was able to flow (overflow?) westward and gradually assume the character of the modern Colorado River. Several such scenarios have been explored by Meek and Douglas (2001), Scarborough (2001), and Spencer and Pearthree (2001). Such locally ponded, interior drainages in northwestern Arizona might be similar to the early Tertiary paleogeographic basin reconstructions in southern Utah described by Goldstrand (1990, 1992, 1994).

Subsequent Pliocene-Pleistocene erosion by the modern Colorado River and its tributaries would have removed evidence of any local sediment depocenters near western Grand Canyon in the area shown on Figure 3. However, evidence of significant ponding during late Paleocene or early Eocene time on the Coconino Plateau near Long Point (Figs. 1 and 3) is suggested by the 30 m thickness of the late Paleocene–early Eocene lacustrine limestones interbedded with fluvial arkoses in a stratigraphic setting similar to that depicted at the base of Figure 4 (Young, 1982, 1999, 2001a, 2001b).

Hualapai Plateau

The Hualapai Plateau structural bench exhibits classic, strike-valley, main-stem drainage with elongate tributaries parallel to the regional dip (Figs. 1, 5, and 6). This structurally controlled drainage system created and still dominates the Hualapai Plateau, a cuestaform landscape initiated by Laramide recession of the Shivwits scarp (Young, 1982, 1985). Scarp recession is facilitated by the stratigraphic position of the more easily eroded Hermit Shale (Figs. 5 and 6). Young (1985) observed that recession of the Shivwits scarp widened the Hualapai Plateau by 8 km between the episode of northeast-flowing Laramide drainage and the younger erosion by the west-flowing Colorado River. This scarp recession measurement is based on the observation that the courses of both the east-flowing, exhumed Laramide canyon and the younger, west-flowing Grand Canyon were constrained to follow the base of the receding Shivwits Plateau scarp, as each successive canyon formed (Hindu Canyon, Grand Canyon, Fig. 1). Dip-slope tributary drainage is the dominant collector of runoff for the incision of the master channel in such a setting. Scarp recession is controlled by the limited runoff from the short obsequent tributaries on the scarp face (Young, 1982, 1985). The fact that successive, opposite-trending drainages developed on the Hualapai Plateau with an 8 km separation can only be explained if the Laramide relief was first completely buried by younger Tertiary deposits (Fig. 4) so that younger Miocene drainage could reform further downdip to the north. Structurally controlled Miocene drainage along the foot of the modern Shivwits scarp would have been initiated by local runoff, regardless of the existence of a throughflowing Colorado River (Fig. 5).

Southwestward flow of Laramide-age drainage (Fig. 1) off the Hualapai Plateau via the Laramide paleocanyon at Peach Springs was incorrectly proposed in McKee et al. (1967) based on preliminary results of field work in progress by Young (1966) that was presented at a 1964 Museum of Northern Arizona symposium, published as McKee et al. (1967). The true northeastward flow direction during the Laramide erosion and subsequent filling (Fig. 4) of ancestral Peach Springs Canyon were later documented by Young (1979, 1982, 1985, 1987). A well-researched chronologic account of these and earlier attempts to understand the evolution of the Colorado River was recently compiled by Powell (2005).

The Laramide through mid-Tertiary history of the southwestern Colorado Plateau as documented by Young (1966, 1979, 1982, 1985, 1987, 1989, 1999, 2001a, 2001b) demonstrates that a regional drainage reversal (northeast to southwest) evolved between middle Eocene time and late Miocene time. Generalized

maps of the Tertiary deposits on the Hualapai Plateau published by Billingsley et al. (1999, 2000) lack the resolution to demonstrate the details of the Laramide history, especially the pronounced post-Laramide disconformity preserved in the thick Tertiary paleocanyon fills (Fig. 4). Young (1966, 1999) provided detailed descriptions of the Tertiary rocks on the Hualapai Plateau and reviewed nomenclature issues relevant to the present discussion.

Speculative Mid-Tertiary Drainage Evolution

When did the episode of northeast-flowing Laramide drainage end? Certainly it must have ceased by the time regional late Oligocene through Miocene volcanism and extensional faulting finally severed the source regions south and west of the Colorado Plateau. The drainage that subsequently evolved in the modern Kanab and Cataract Basins could have only flowed, or overflowed, westward toward the Hurricane fault and merged with the evolving drainage on the Hualapai Plateau. A postulated northwestern outlet for an ancestral Colorado River between the Kaibab Upwarp and the Shivwits Plateau in Muddy Creek time (Lucchitta, 1989) has been effectively ruled out by Pederson (2001, 2005). However, the obvious structural influences that clearly shaped tributary evolution on the western Colorado Plateau have yet to provide a unique solution as to when or where the emerging drainages joined, ponded, or exited the Hualapai Plateau.

An unresolved issue related to the regional drainage reversal is how the Laramide drainage, following the northeast trend of the Hurricane fault zone, was replaced by a drainage system flowing westward. This is partially explained by the fact that the Hurricane fault zone was originally the location of an east-verging Laramide monocline, but during Miocene extension, it became converted to a down-to-the-west normal fault. Regional topographic slope reversal was also enhanced by Miocene Basin and Range extension, which allowed southwestward back-tilting of the upraised Laramide margin of the plateau (Young, 2001a).

Following these events, the inherited Laramide physiography must have predetermined the location of a shallow precursor valley along the modern Colorado River corridor between the Hurricane fault and the Grand Wash Trough on the Hualapai Plateau along the base of the Shivwits Plateau scarp (Figs. 1, 5, and 6). The existence of such a pre–Colorado River, middle Miocene drainage, including a knickpoint incising itself headward from the edge of the Colorado Plateau (Grand Wash Trough), is an inevitable product of the relict Laramide physiography (Fig. 1). Such structurally controlled, strike-valley drainage development on the western Hualapai Plateau, preceding the onset of a throughflowing Colorado River, would have prepared the way for the ultimate integration of the headward Rocky Mountain tributaries of the Colorado with the downstream section between the Grand Wash Trough and the Kaibab Upwarp.

COLORADO RIVER EMERGENCE AND CONSTRAINTS

It has been clearly established that a throughflowing, integrated Colorado River did not flow from the Grand Wash Trough area to the Gulf of California until between ca. 5.5 and 4 Ma (House et al., 2005; Faulds et al., 2001a). Estimates of Colorado River Pleistocene incision rates from studies by several workers indicate that the Colorado River could have eroded a deep canyon into the Colorado Plateau within the more limited time available during the Pliocene Epoch and the subsequent 2 million years of wetter Pleistocene stadials (Young and Spamer, 2001). However, the mere demonstration of rapid canyon erosion upstream from the Hualapai Plateau during Pliocene-Pleistocene time does not constrain the earliest initiation of headward erosion along the Hualapai Plateau margin. There is no clearly documented evidence for the exact beginning of early to middle Miocene drainage incision by headward erosion along the Hualapai Plateau margin between the onset of Basin and Range extensional faulting and the appearance of a throughflowing Colorado River, a period in excess of 11 m.y. However, it is unlikely that the Hualapai-Coconino Plateau region failed to develop some kind of integrated drainage system for such a long interval.

Elston and Young (1991) describe how post–Basin and Range headward erosion at the southern edge of the Hualapai Plateau in the Truxton Valley (Fig. 1) has progressed 32 km eastward into the plateau margin, and they postulate that similar headward erosion was likely to have been initiated along the Hualapai Plateau margin from Grand Wash Trough following the development of significant extensional relief on the prominent Miocene fault scarps. Faulds et al. (2001b) also speculated that headward erosion during and following Basin and Range faulting probably would have initiated mid-Miocene drainage along the western edge of the Colorado Plateau that ultimately would have contributed to the gradual emergence of the modern Colorado River drainage system.

The details of the events from middle Eocene through Oligocene time on the southwestern Colorado Plateau are not well constrained due to the scarcity of datable horizons within the Cenozoic deposits (Elston and Young, 1991). A widespread fluvial conglomerate capped by 19.9 Ma basalts (Billingsley, 2001) is the only post-Laramide evidence for mid-Tertiary plateau drainage (Fig. 4). The Buck and Doe Conglomerate (Young, 1966, 1999) indicates that aggradation by local streams on Hualapai Plateau proper probably dominated the post-Laramide to early Miocene interval. This conglomerate and the younger Miocene volcanic sequence obliterated the last vestiges of Laramide relief (Young, 1966, 1989).

The better-documented, southwestern Colorado Plateau mid-Tertiary chronology, based on dated volcanic rocks, begins ca. 24 Ma (Young and McKee, 1978), approximately coincident with the early onset of Basin and Range extension across the much broader region (Spencer et al., 1995). Constraints on Hualapai Plateau events can be reconstructed only from the limited chronology depicted on Figure 4.

When structural and topographic relief in excess of 1000 m developed at the Hualapai Plateau margin in the Lake Mead–Grand Wash Trough region between 16.5 Ma and 13 Ma (Faulds et al., 2001b), initiation of renewed (post-Laramide) headward erosion and incision along the western Hualapai Plateau must have begun (Elston and Young, 1991). This assumption is supported by numerous field studies that demonstrate a close temporal relationship between structural deformation and the resulting relief-driven erosion. Reviews such as that by Lamb et al. (2005) and Faulds et al. (2001b) suggest that erosion and deposition proceed contemporaneously (syntectonically) with structural deformation. It seems intuitive that sedimentary filling of fault-bounded basins implies severe erosion of adjacent scarps, as would have been the case with the margin of the Hualapai Plateau, irrespective of the existence of the modern Colorado River.

Drainage-Basin Limits and Erosion Potential

The drainage area of the Hualapai Plateau that supplies runoff to the modern Colorado River is ~2000 km². The additional area added to the Hualapai Plateau drainage by the upstream tributaries between the Hurricane fault and the headward reaches of Kanab and Cataract Creeks increases the basin dimensions to more than 13,000 km². The erosion potential of this large subbasin, restricted to the plateaus west of the Kaibab Upwarp, is sufficient to initiate the incision of a Colorado precursor canyon as depicted on Figure 5. The impressive dimensions of the modern Kanab and Cataract Creek canyons themselves (Fig. 3) illustrate the erosive power that is available within much smaller subbasins. The relief necessary to initiate canyon incision along the western edge of the Hualapai Plateau at the Grand Wash Trough is documented by the structural relief preserved under the Muddy Creek–age sediments, a minimum of 600–1200 m. This physiographic setting virtually guarantees that a modest Miocene canyon would have been initiated across the Hualapai Plateau in the present location of the modern Grand Canyon, even if minimal precipitation values are assumed.

The ages of lavas capping the Tertiary sediments on the Hualapai Plateau imply that such a drainage system probably did not become significantly incised to form a canyon until after 19 Ma (Young, 1989, 2004). This is based on the observation that fluvial aggradation and Laramide canyon burial, rather than erosion, characterized most of the southwestern Hualapai Plateau (Fig. 4) until the Miocene volcanism ceased (Young, 1966). There is also paleohydrologic evidence from cave speleothems in the Redwall-Muav aquifer that suggests the western Grand Canyon is at least 19 million years old and that it becomes younger upstream (Polyak et al., 2004).

The final means of integration of any hypothetical western drainage system with the upper Colorado River to form the modern Colorado River is admittedly problematic and poorly constrained in time. Previous theories of how this integration occurred (McKee et al., 1967) have invoked the process of headward erosion from the west to the east, across the Hurricane fault zone. Critics of this theory argue that headward migration of a drainage divide is a very slow and inefficient process (Spencer and Pearthree, 2001). However, the events described in this discussion do not involve only simple divide migration. The canyon-forming process is more similar to headward migration of a major knickpoint located between structurally separate basins on either side of the Hurricane fault zone, not unlike the regional knickpoint described by Karlstrom (2004) near Lees Ferry.

The subbasins between the Hualapai Plateau margin and the Kaibab Upwarp are independently defined by the preserved Laramide structural relief of each region (Figs. 1 and 3). Local runoff from these adjacent subbasins eventually must have evolved into a single, coherent drainage system. The possibility of a period of temporary ponding of Eocene–early Miocene(?) drainage east of the Hurricane fault zone on the Coconino Plateau before the Kanab-Cataract Creek systems spilled westward onto the Hualapai Plateau is a minor issue of timing that is irrelevant to arguments in the present model. The modern topography of the Hualapai Plateau surface led to northwest-flowing Miocene surface runoff concentrated along the base of the Shivwits scarp (Figs. 5 and 6) following Basin and Range faulting, in contrast to the physiographic setting in Laramide time. If it can be assumed that the evidence presented so far favors a Miocene emergence and eventual incision of local northwest-flowing drainage on the Hualapai Plateau, the potential impact of such a system can alter assumptions about the sedimentation history of the Grand Wash Trough.

IMPLICATIONS OF A HUALAPAI PLATEAU CANYON OF MIOCENE AGE

Discharge Estimates

A canyon similar to the one depicted on Figure 5 is likely to have been initiated in the considerable time available from late Oligocene through late Miocene time for the reasons enumerated already. At an early stage, this drainage system would have been relatively shallow, especially in its upstream reaches, limited by the gradual development of Basin and Range extensional relief and annual runoff. However, once the relief increased to the maximum amount indicated by the structural offsets in the Grand Wash Trough (Fig. 2), the incision of a deeper western Hualapai Plateau canyon in Miocene time seems inevitable. There is an interval of 10 m.y. or more between the creation of appreciable relief at the Hualapai Plateau margin and the evidence for the integration of the modern Colorado River. If the postulated precursor canyon became sufficiently incised during some portion of this interval, the resulting canyon topography can simplify some of the issues related to the nature of upwardly fining facies changes within the Grand Wash Trough sediments, culminating in the deposition of the 300-m-thick Hualapai Limestone. A realistic appraisal of the potential impact of such an ancestral western Grand Canyon requires an estimate of the average discharge of the postulated drainage basin and the inferred sediment load.

Descriptions of the Muddy Creek–age sedimentary "rocks of the Grand Wash Trough" near the current mouth of the Grand Canyon (Lucchitta, 1966, 1972) emphasize the lack of coarse fluvial clasts indicative of a large river with sediment sources compatible with the existing Colorado River. However, if a postulated precursor canyon existed on the western Hualapai Plateau during Muddy Creek time, an alternative scenario is possible. An early phase of such an incising canyon would not necessarily have a large sediment load. The drainage system west of the Kaibab Upwarp probably would support only an intermittent or ephemeral stream for the following reasons. The majority of the modern Colorado River discharge comes from the Rocky Mountain headwaters. Relatively little runoff is derived from Arizona tributary canyons.

The drainage area of the Colorado River Basin upstream from the Grand Canyon gage near Bright Angel Creek is 356,900 km^2. The 140 km river distance between the Lees Ferry gage near the Arizona-Utah border and the downstream Grand Canyon gage consists of 78,000 km^2, or 22% of that drainage-basin area. Despite this 22% increase in area, there is a only a 4% increase in the average annual historic (predam) discharge on the Colorado River between Lees Ferry and Grand Canyon. The predam average discharge at Lees Ferry was ~500 m^3/s.

The Little Colorado River drainage area of 68,635 km^2 typically contributes less than 1% of the discharge measured at Grand Canyon, although it is over 19% of the Colorado River Basin area upstream from the Grand Canyon gage. Downstream from Grand Canyon gage, the additional increase in drainage-basin area over the 220 km river distance between Grand Canyon and the Hurricane fault adds only 29,800 km^2 (8.3%) more drainage area to the basin. These approximate area comparisons indicate that runoff and groundwater flow to the Colorado River between the Grand Canyon gage and the Grand Wash Trough would probably be less than 1% of the average discharge of the predam modern Colorado River system, or ~5 m^3/s. Therefore, any ancestral drainage system west of the Kaibab Upwarp on the Hualapai, Kanab, and Coconino Plateaus would produce only a correspondingly small fraction of the modern Colorado River runoff. The clastic sediment load in such a drainage system, compared to the modern Colorado River, would be reduced by a proportional amount.

Estimated Sediment Input

Much of the surficial bedrock exposed throughout the proposed Hualapai-Kanab-Cataract basin (Figs. 1, 3, and 5) consists of carbonate lithologies, leading to an even greater relative reduction in clastic sediment output from the lower basin as contrasted with upstream reaches of the modern Colorado River. In late Muddy Creek time, as the Grand Wash basin filled and the adjacent canyon system deepened and expanded, the Hualapai Plateau drainage system would have contributed little siliciclastic sediment, but the river discharge would have been high in dissolved calcium carbonate.

A regional transition to more humid conditions in the Southwest occurred near the Miocene-Pliocene transition (Axelrod,

1950; Hunt and Elders, 2001), and the Pleistocene Epoch was clearly associated with increased moisture. The increased rainfall also may help to explain the transition to a shallow lacustrine environment in Hualapai Limestone time.

The Grand Wash Trough lacked a significant external outlet during Muddy Creek time, as indicated by the interior basin stratigraphy and by the similar lacustrine facies in the adjacent basins west of the Colorado Plateau. As the Grand Wash Trough filled with sediment and the climate became less arid, the Grand Wash Trough depositional environment evolved from fluvioclastic to the freshwater lacustrine conditions recorded by the Hualapai Limestone (Faulds et al., 2001a). The presence of a postulated Colorado River precursor, lake-filled canyon is consistent with this transition and helps to account for the observed lithologic changes, as well as for the lack of a massive delta at the canyon mouth. The presence of such a canyon system (Fig. 5) feeding increased runoff into the Grand Wash Trough would have introduced a long narrow lake arm extending from the Grand Wash Trough well up the canyon toward the Hurricane fault zone as the Hualapai Limestone lake deepened (Fig. 7). The elevation of the top of the preserved Hualapai Limestone section near the mouth of Grand Canyon is presently 900 m (Fig. 2). The water level of the Hualapai Limestone lake in the Grand Wash Trough would have been no lower than this elevation when the uppermost limestone formed. A lake with a surface at this elevation, extending into the postulated canyon, would have submerged any exposed Precambrian rocks or Cambrian sandstones (Fig. 6), leaving carbonate strata as the dominant bedrock type exposed along the narrow lake as well as on the adjacent Hualapai Plateau. Most of the canyon would be filled with water to a level that would submerge the strata below the Muav Limestone (Fig. 6). The presence of a narrow canyon lake also would shift any clastic delta of middle to late Miocene age well upstream into the canyon (Fig. 7), and it would create an efficient sediment trap for the limited siliciclastic bed load and suspended load of this relatively restricted basin, with its limited discharge. Evaporation would also reduce the discharge reaching the Grand Wash Trough and contribute to the carbonate saturation of the lake water. This scenario would prevent most, if not all, of the upstream coarse clastic sediment from reaching the present mouth of the canyon at the Grand Wash Trough.

Carbonate Facies Shift

One of the curious issues relating to Hualapai Limestone deposition is how to explain the increased carbonate input to the basin following the widespread accumulation of clastic sediment prior to late Miocene time. The possible contribution of spring discharge from Paleozoic limestone aquifers has been suggested by Hunt (1969, p. 116), by Faulds et al. (2001a), and by Pederson (2005). The scenario described here also would be compatible with a change from clastic to carbonate deposition. Surface runoff and groundwater entering the Grand Wash lake through the
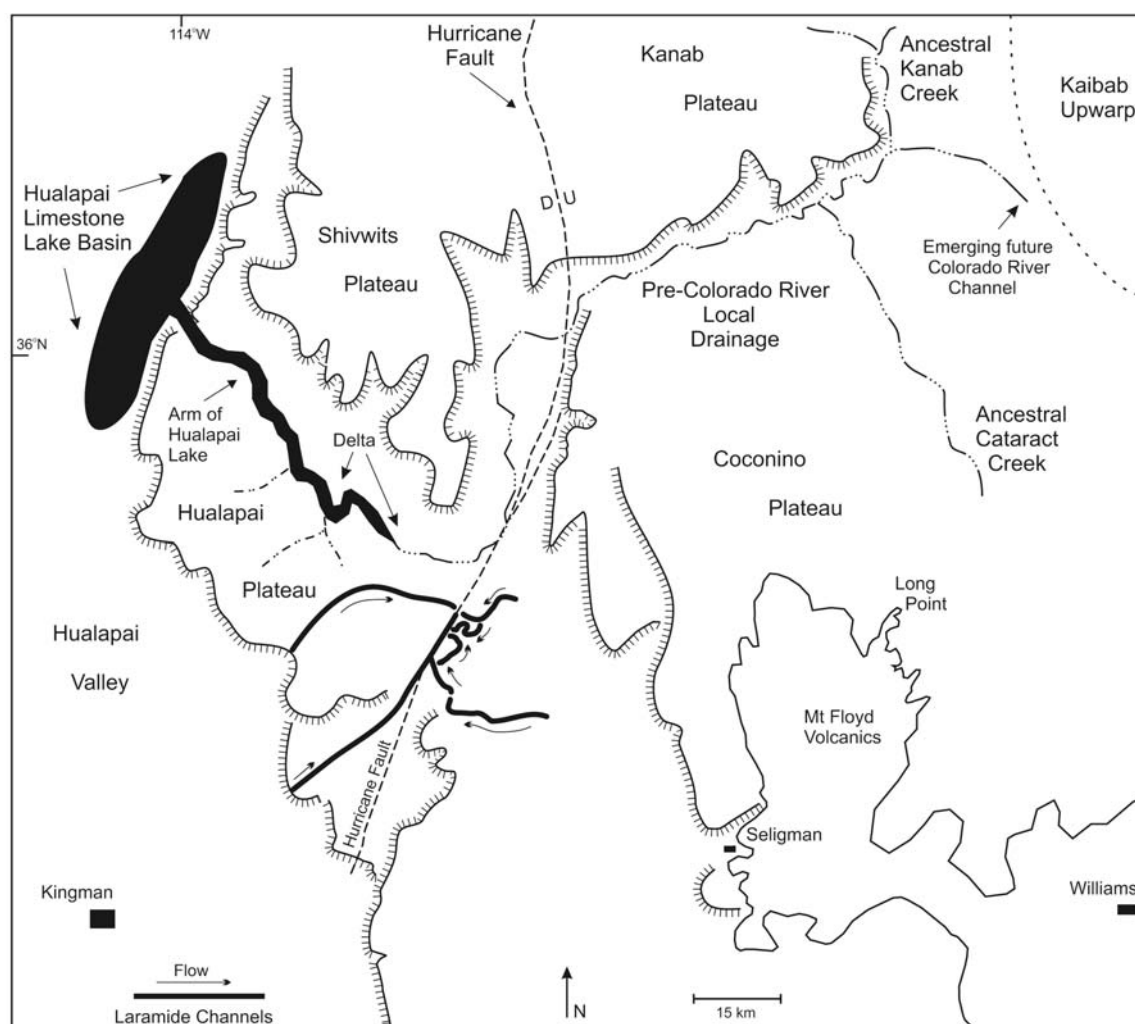
Figure 7. Hypothetical depiction of middle-to-late Miocene Hualapai Plateau canyon forming restricted arm of Hualapai Limestone lake (black). Length of lake is meant to be suggestive only and may have been longer or shorter. Ancestral Kanab and Cataract Creeks illustrate approximate extent of additional pre–Colorado River drainage basin supplying runoff to Hualapai Plateau in early to middle Miocene time from area west of Kaibab Upwarp. Combined area of basin depicted currently accounts for ~1% of predam Colorado River discharge.

Hualapai Plateau ancestral canyon, including the extensive Redwall karst system, would be carbonate enriched, compatible with the facies change recorded by the Hualapai Limestone.

Faulds et al. (2001a) also point out that the Grand Wash Trough and adjacent basins that contain the Hualapai Limestone are flanked to the north and south by basins of similar ages where gypsum and halite deposition prevailed, rather than carbonates. They interpret this as an indication that the Hualapai Limestone axial basins had a significant inflow of freshwater, whereas the flanking basins received only periodic overflows and were dominated by evaporation. This setting seems compatible with the proposed Hualapai Plateau drainage scenario.

In this admittedly simplistic paleogeographic model, the carbonate rocks that dominate the restricted upstream basin geology of the Hualapai and Coconino Plateaus would have increased the dissolved carbonate input to the Muddy Creek basin; this is compatible with the switch to the carbonate-rich facies preserved in the Hualapai Limestone. During this late Muddy Creek interval, with no integrated upper Colorado River, the clastic sediment supplied to any delta confined within the upper reaches of the narrow canyon lake would be much less than at the modern Colorado River delta that is building into Lake Mead. Removal of all the evidence for such a relatively small, canyon-bound delta deposit would have been efficiently accomplished by the integrated Pliocene-Pleistocene flow of the younger, throughflowing Colorado River, given the narrow, elongate shape of the proposed lake and the much greater erosive power of the modern river.

Additional Geologic Evidence

The ages and evolution of western Grand Canyon spe-leothem deposits as described by Polyak et al. (2004) are com-patible with this model of an ancestral Hualapai Plateau canyon that is of middle Miocene age in the west and becomes younger to the east. Patchett and Spencer (2001) and Crossey et al. (2006) document and discuss implications of the complex geochemistry of Colorado River water and the isotopic evidence preserved in lacustrine and travertine deposits in the Lake Mead–Hualapai Plateau region.

OTHER HEADWARDLY ERODING BASINS

An analogous geologic setting that compares favorably with the postulated Hualapai Plateau scenario is present 180 km south-east of the Hualapai Plateau along the Mogollon Rim where west-flowing West Clear Creek exits the Colorado Plateau into the Verde Valley (Fig. 8). A regional description of Mogollon Rim drainage and history is contained in Holm (2001). The vertical relief near the mouth of West Clear Creek canyon where it enters the Verde Valley is 700 m. The eastward expansion of the West Clear Creek drainage basin has captured and diverted some of the headwaters of east-flowing East Clear Creek (Fig. 8). West Clear Creek is little more than 35 km long and has a drainage area of only ~900 km². The bedrock in the basin consists of eroded Per-mian strata overlain by Miocene lava flows dated at 9–10 Ma. Despite this much smaller drainage area as compared with the Hualapai Plateau, the mouth of West Clear Creek canyon is approximately the same width as the mouth of the modern Grand Canyon at the Grand Wash Cliffs. The depth of the West Clear Creek canyon (610 m) is two-thirds of the depth of the Grand Canyon at its mouth (1065 m). These strikingly similar propor-tions, combined with the similar geologic setting, demonstrate that a relatively small drainage basin, given sufficient relief, can excavate a significant canyon in 10 m.y. or less. The existence of
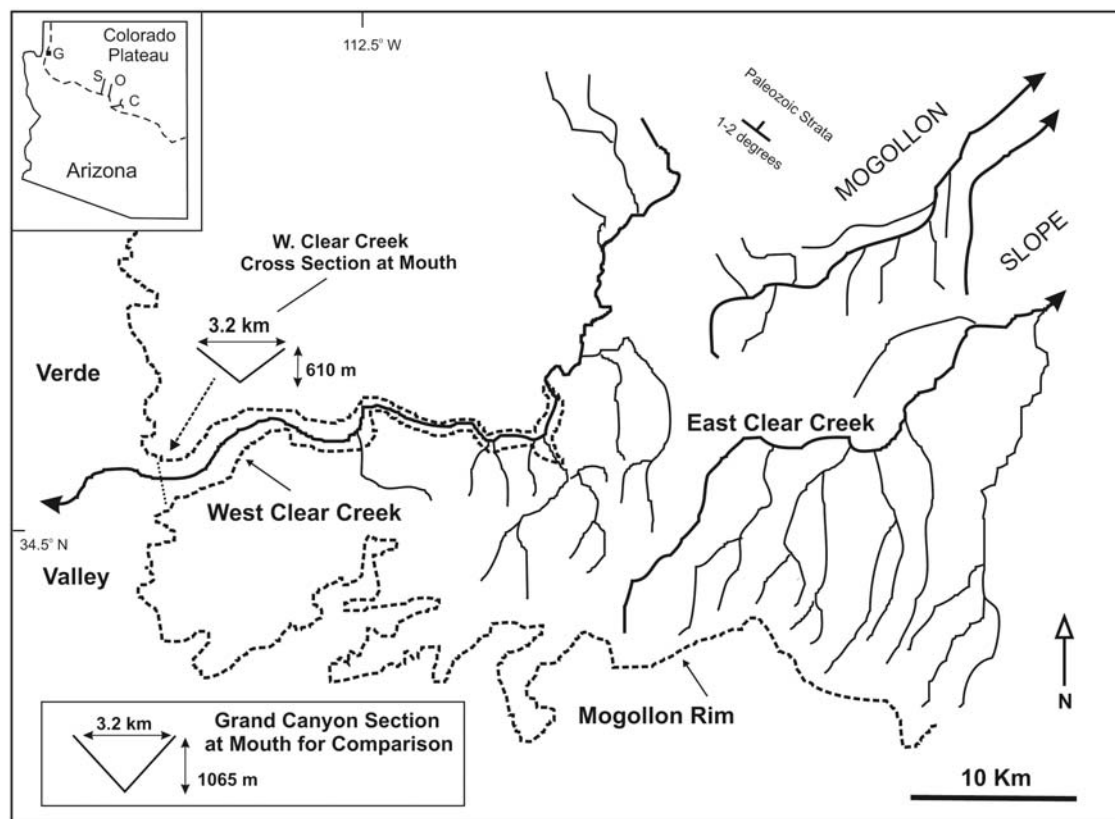

Figure 8. Example of barbed (captured) headwardly eroding drainage of West Clear Creek along Mogollon Rim on east side of Verde Valley. Relatively short (35 km) and modest-sized drainage basin of West Clear Creek (900 km²) has diverted head-ward tributaries of east-flowing East Clear Creek and eroded a canyon as wide as the mouth of Grand Canyon and two-thirds as deep. Local bedrock is thin, mid-Miocene volcanic flows disconformably overlying Permian strata, similar to Grand Canyon section on Hualapai Plateau. This example illustrates the capacity of small drainage basins to create relatively large canyons in relatively short time intervals. Inset location diagram: G—Grand Canyon mouth; C—West Clear Creek; S—Sycamore Canyon; O—Oak Creek Canyon.

such a large canyon, formed by a relatively small basin in a semi-arid region, implies that vertical canyon incision is an efficient process, and that headward erosion and knickpoint migration are significant factors, despite the seeming inefficiency of headward divide migration. Several other large canyons have formed along the southwestern margin of the Colorado Plateau between the Verde Valley and the Hualapai Plateau, such as the well-known localities at Oak Creek and Sycamore Canyon (Fig. 8). These drainages all are deepening and expanding headward onto the Colorado Plateau in directions nearly opposite to the regional dip of local bedrock. The Hualapai Plateau Miocene physiography and structure were much more conducive to drainage evolution and incision controlled by the regional strike of resistant scarps.

CONCLUSIONS

A postulated pre–Colorado River canyon on the Hualapai Plateau at the base of the Shivwits Plateau scarp is a predictable and necessary consequence of the regional rock structure, Laramide history, and the simple mechanics governing surface runoff and drainage-basin evolution. The proposed model for the evolution of the western Grand Canyon does not resolve the issue of how the upper and lower Colorado River basins finally became fully integrated between the Rocky Mountains and the Gulf of California. It can provide a potential explanation for the gradual, progressive development of the western Grand Canyon topography. It eliminates the need for erosion of the entire depth of the western Grand Canyon in the relatively short time between the end of Hualapai Limestone deposition (5.97 Ma) and the probable age of the oldest Colorado River gravels (6–5 Ma). Furthermore, the scenario described here is a logical consequence of the structural and topographic landscape that resulted from Laramide uplift and Miocene extension. It is unrealistic to assume that this, or any other, terrestrial landscape would not undergo continuous evolution and erosional modification from late Eocene through middle Miocene time.

The appearance of a carbonate-rich facies, such as the Hualapai Limestone, is compatible with a wetter Pliocene-Pleistocene climatic trend superimposed on the proposed physiography and carbonate-dominated bedrock exposures across the adjacent Hualapai, Coconino, and Kanab Plateaus. Whatever the final resolution of the issues relating to the integration of the upper and lower Colorado River system, the explanations are likely to be compatible with a lengthy episode of gradual landscape evolution, rather than short, episodic events forced to fit an incomplete chronology. While episodic tectonic or climatic events may cause temporary changes in local base levels or incision rates, the gradual erosional evolution of the regional landscape must proceed in accordance with the gravitational potential associated with the preexisting rock structures and natural slopes. The evolution of the modern Colorado River Basin from the Rocky Mountains to the Gulf of California should be envisioned as a time continuum during which significant interruptions occurred, but where the contributions of evolving subbasins were an integral part of a more gradual process. The Colorado River course should be viewed as resulting from the interactions among its many evolving subbasins, rather than as the master control of the process. While this may seem obvious, the evolution of the Colorado River system is viewed too often as a simple matter of uplift and erosion with insufficient attention to a more holistic, four-dimensional approach.

ACKNOWLEDGMENTS

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